Demand Response Potential of Electricity End-users Facing Real Time Pricing

Ma, Yiqun

Publication date:
2016

Citation for published version (APA):
Ma, Y. (2016). *Demand Response Potential of Electricity End-users Facing Real Time Pricing*. (SOM Research Reports; Vol. 16019-EEF). University of Groningen, SOM research school.

faculty of economics
and business

16019-EEF

Demand Response Potential of Electricity End-users Facing Real Time Pricing

Yiqun Ma

SOM is the research institute of the Faculty of Economics & Business at the University of Groningen. SOM has six programmes:
- Economics, Econometrics and Finance
- Global Economics & Management
- Human Resource Management & Organizational Behaviour
- Innovation & Organization
- Marketing
- Operations Management & Operations Research

Research Institute SOM
Faculty of Economics & Business
University of Groningen

Visiting address:
Nettelbosje 2
9747 AE Groningen
The Netherlands

Postal address:
P.O. Box 800
9700 AV Groningen
The Netherlands

T +31 50 363 9090/3815

www.rug.nl/feb/research

Demand Response Potential of Electricity End-users Facing Real Time Pricing

Yiqun Ma
University of Groningen, Faculty of Economics and Business, Department of Economics, Econometrics and Finance
Ym903@uowmail.edu.au

Demand Response Potential of Electricity End-users Facing Real Time Pricing

Yiqun Ma[1]

Faculty of Economics and Business, University of Groningen

4 October 2016

Abstract

Because of the increasing supply of intermittent renewable energy sources, demand response by end-users may be helpful to balance electricity networks and to prevent network bottlenecks. This paper estimates the hourly potential of price-based demand response in a number of European countries, especially for the residential end-users, using data from the real-time market. For that purpose, we investigate the hourly own and cross elasticities in different European countries. Based on these elasticities, historical spot prices as well as a number of technical constraints, we construct a price-based optimization model to identify the hourly potentials of price-based demand response. The estimation results show that the magnitudes of elasticities are relatively small, while the hourly potentials in the residential sector are not significantly higher than those in industrial and tertiary sector. This suggests that the potential of price-based demand response in the residential sector to deal with the increasing supply of renewables is small.

Keywords: Electricity market; Price-based demand response; Intermittent generation

---

[1] This paper is written as part of the research project "Redesigning the electricity market in order to facilitate the transition towards a sustainable energy system", financed by NWO and various stakeholders in the Dutch energy industry. The author thanks the members of the Valorization Board as well as the Scientific Advisory Board for their input during this project. The author also acknowledges APX, E. ON NL, E. ON UK, E. ON DE, E. ON SE, E. ON DK, Vattenfull, Fjordkraft for the provision of historical data on spot prices. The author, however, is fully responsible for the contents of this paper. Email: ym903@uowmail.edu.au.

1. Introduction

A fundamental issue in the electricity market is to balance demand and supply and to ensure reliability. This issue is becoming more severe because of the increasing supply of intermittent renewable energy. One possible option for solving this issue is to introduce demand response (DR). DR, which includes price-based and incentive-based options, attempts to alter the timing (load shifting) and the total consumption level of electricity (load shedding). In practice, the loads of end-users are flexibly adjusted to the availability of fluctuating renewable energy sources. This short run adjustment requires some minutes to a few days. Recent studies on the estimation of DR potential focus on the load reduction over a long time horizon, such as the annual potential of DR (Feuerriegel and Neumann, 2014 ; Gils, 2014; Paulus and Borggrefe, 2011), and the large end-users, such as the industrial and commercial customers. Residential users facing the price-based DR should be more sensitive to price signals in the short run. However, assessments of the potential of price-based DR for the residential users in the real-time market are sparse. In the residential sector, the consumption preferences and lack of measurement data make it difficult to examine the effect of DR.

Examining the hourly potentials of price-based DR in the residential sector is important for at least two reasons. Firstly, this estimation can help policy makers to acknowledge the effect of price responsiveness of residential customers on accommodating excess demand of electricity in the short run. For example, if price changes in the spot market would be fully observed by residential users, peak consumption can be largely shifted or shed in case of high prices. Secondly, the estimation of the hourly potentials of price-based DR relates to the justification of excess investment in generation capacity. Intuitively, if peak consumption can be regularly and reliably reduced, capacity investment can also be reduced.

This study aims to identify the hourly potential of price-based DR in a number of European countries (Germany, the Netherlands, the United Kingdom, Denmark, Norway, Sweden and Finland[2]), especially in the residential sector. The estimation of hourly potential of price-based DR depends on price elasticities and a price-based model. Firstly, we identify

[2] We choose these countries because they are all located in the northern part of Europe, while they have fairly different characteristics of electricity consumption.

the characteristics of these users, considering main technical restrictions, such as the time availability of DR (time for load shifting and shedding of a day), technical constraints (installed capacity, utilization rate and revision rate) and the impact of outdoor temperatures. Secondly, to estimate the potential of price-based DR, the hourly own and cross elasticities are determined by the method in Kirschen et al. (2000). Price elasticities reflect the end-user responsiveness of load adjustment to changes in prices. Based on price elasticities, spot prices and technical constraints, a price-based model for minimizing the costs of an electricity retailer can be developed. Unlike the model in Gils (2014) where the potential is estimated by the load profiles, our model focuses on price changes and price elasticities in the real-time market.

After assuming that all end-users face real-time prices, results from the proposed model show that the maximum hourly potentials of price-based DR in industrial, tertiary and residential sectors can be 0.28%, 0.08% and 0.26% of peak loads in 2014. The hourly potentials in the residential sector are not significantly higher than those in industrial and tertiary sectors. Simultaneously, a high correlation between changes in spot prices and dynamics of the hourly potentials of price-based DR in the residential sector is evident. Notably, the overall hourly potential of price-based DR is highest in the morning.

These results have some policy implications for balancing electricity demand and supply. Firstly, in addition to increasing investment in generation capacity, the estimated hourly potential shows that the price-based DR can provide some sources to balance electricity demand and supply. Secondly, policies of load management should primarily focus on the electrical appliances in different sectors associated with large potentials of price-based DR.

This study is organized as follows. Section 2 explores the characteristics of specific price-based DR options. Section 3 reviews the literature on DR potential and price-based DR. Section 4 delivers a methodology for assessment. Section 5 presents numerical analyses. Section 6 concludes and provides some policy implications.

2 Price-based DR

2.1 Policy options

Price-based DR is designed to promote the low consumption of end-users by setting continuous high price signals of electricity (Hurley, Peterson & Whited 2013). Based on smart meters, this low consumption can be realized by load shifting and shedding. Options of price-based DR are time of use (TOU), critical peak pricing (CPP) and real-time pricing (RTP). Notably, load modifications in the price-based options are voluntary and not dispatched by a system operator (except for the aggregation of small contracts) (Hurley, Peterson & Whited 2013).

As demonstrated by Albadi and El-Saadany (2007), the effect of price-based DR depends on price signals. More specifically, the price signals change in accordance with the time-varying generation costs of electricity (energy prices), increasing price flexibility (USDE 2006). These price signals in different time blocks shift electricity consumption and are predetermined for a period of several months and years. In general, the prices during peak periods are higher than those during off-peak periods. The critical peak pricing adds a higher pre-specified price of electricity usage into the time of use prices or normal flat prices. Hence, informed costumers are allowed to respond to the price changes in critical periods. The customers in the critical peak pricing receive a price discount during off-peak period (USDE 2006). In a similar manner, the real-time pricing charges the end-customers with more fluctuating rates based on the spot prices. The prices under the real-time pricing are only formed on a day-ahead or hour-ahead basis, aiming at industrial customers due to the high costs of price evaluation and smart metering (Celebi, Fuller 2007).

2.2 Price-based DR in European countries

Time of use (an option in the price-based DR) is used in Denmark, Finland and the United Kingdom, while it is rare in Germany, the Netherlands, Norway and Sweden. More specifically, Denmark installed 110,000 metering systems to serve 550,000 customers with the retail contracts of time of use in 2010. In 2008, the Finish main electricity utility invested in a smart metering reading system to automatically read, control and manage 60,000 metering data from industrial customers (Torriti, Hassan & Leach 2010). In the United Kingdom, almost 4,500,000 large industrial and commercial customers participate in the time of use. Using reading and communication technology, British customers can respond to a time-differentiated rate in the retail market (Torriti, Hassan & Leach 2010).

In short, the implementation of price-based DR is limited in Europe. The time of use in the price-based DR is primarily adopted by large industrial end-users rather than residential customers.

3. Literature review

In case of increasing supply of intermittent renewable energy sources, DR may play an important role in balancing electricity in the short run. To shed the light on the magnitudes of DR potentials in European countries, we review existing literature on the potential estimations in industrial, tertiary and residential sectors.

3.1 DR potential

To assess the theoretical potential of DR in Europe, Gils (2014) built load shifting and shedding models based on different load profiles of customers. These load profiles characterize the impacts of different temperatures and seasons on loads of electrical processes and appliances in industrial, tertiary and residential sectors. Using installed capacity and the assumed time availability of DR, Gils (2014) calculates the potentials of DR for allowed shifting and shedding loads in three sectors in Europe. The identified annual potentials of DR amount to a minimum load reduction of 61GWh and a minimum load increase of 68GWh on average. More specifically, the potentials of DR in three sectors are not constant, with industry accounting for 5GWh—33GWh, tertiary sector 21GWh—45GWh and residential sector 43GWh—209GWh.

The DR potential is the key for power system balancing and efficiency. Dena (2010) and Klobasa (2007) focus on the interaction of power production from intermittent renewable energy sources and DR to improve system efficiency. Klobasa's simulation results in

Germany found that 1500MW of additional minute reserve power and 2.85 €/MWh of additional balancing cost were necessary in 2005 with 17GW wind power installed. However, if 10% of the production capacity for DR is used in the pulp and paper industry, about 4% of electricity costs can be lowered. These results are similar to those in Feuerriegel and Neumann (2014). They find that a full utilization of the potential of DR in Germany can reduce peak costs and price volatility by 14.35% and 7.74%.

Although Gils (2014) and Klobasa (2007) presented the annual potentials of DR using load-based calculation for industrial, tertiary and residential sectors, the real-time potential of DR remains unknown. Moreover, the potential of DR varies significantly throughout the day, especially in the residential sector. Thus, related to Gils (2014) and Klobasa (2007), this study estimates the real time potentials of price-based DR in three sectors, undertaking price-based estimation based on the technical constraints and the characteristics of load profiles.

3.2 Price-based DR

The price-based DR is designed to shift and shed electricity consumption, including time-of-use (TOU) and real-time pricing (RTP). Understanding the relationship between TOU, RTP and price elasticities (own and cross elasticities) is crucial to estimate the potential of DR. Most existing literature regarding price elasticities focuses on TOU (Al-Faris 2002, Beenstock, Goldin & Nabot 1999, Filippini, Pachauri 2004, Holtedahl, Joutz 2004). The proposed own elasticities vary from –0.04 to—0.18. In addition, the real-time price elasticity of electricity in the Netherlands is estimated by Lijesen (2007). The identified real-time elasticity in the Netherlands with –0.0043 is relatively smaller than that in TOU. Notably, in Beenstock et al. (1999), the price elasticity in the residential sector is larger than that in the industrial sector.

In summary, little is known about the real-time potential of price-based DR in industrial, tertiary and residential sectors. Based on these results, we use the own and cross elasticities from own calculations, as well as data of spot prices to estimate the hourly potentials of price-based DR (load shedding and load shifting) in industrial, tertiary and residential sectors.

4 Estimation of the hourly potential of price-based DR

This study quantifies the hourly potentials of price-based DR in the European countries, using bottom-up approach. This approach focuses on production processes and electrical appliances, as electricity is a necessary input in industrial, tertiary and residential sectors. In addition, time of day, temperature and weather conditions have impacts on electricity loads. In this analysis, the hourly potential of price-based DR is examined in three ways. Firstly, specific electric processes and appliances for DR are specified. Secondly, the characteristics of load profiles in three sectors are identified. Thirdly, installed capacities of appliances and models of estimating the hourly potential of price-based DR are clarified. The used assumptions and parameters are related to those in Gils (2014).

4.1 Flexible loads in three sectors

This study assesses loads of 12 different processes and appliances. Notably, flexible loads are constrained by technical limits, production processes and installed capacities. In energy-intensive industries, such as aluminum, copper, zinc and steel marking, any load adjustment is not available (Gils 2014). DR activities in energy-intensive industries are assumed to be not allowed. According to the investigation in Olsen et al. (2014), the load curves of manufacturing production and pumps in water supply in 24 hours remain fairly flat. Moreover, productions in most industrial companies require non-stop operations. Hence, only load shedding is assumed to be allowed in the manufacturing production in 24 hours. Accordingly, due to the surveyed peak hours of loads and limited business hours in the commercial sector (Olsen et al. 2014), it is assumed that most of available time of load shedding is limited during 8:00—20:00 (peak hours). Moreover, due to the use of thermal storage, pre-heating and pre-cooling are applicable in the tertiary sector (Olsen et al. 2014). Hence, load shifting in the tertiary sector is only allowed for loads of commercial heating and air conditioning. In the residential sector, due to the overall consumer preferences and time-dependency, only load shifting for wet appliances (washing machine, dryer) and load shedding for cold appliances (refrigerator) are available (Abdisalaam et al. 2012). Other appliances in households cannot be controlled by smart metering devices. Notably, the hourly magnitudes of load shifting and shedding are measured by cross and own elasticities. Thus, the load shifting is assumed to allow both load advance and delay. Table 1 provides descriptions of the DR for processes and appliances in three sectors and their assumed values.

Table 1: Overview of properties of processes and appliances

Sector	Process/Appliance	DR	t_{shift} (h)	t_{shed} (h)	*Season*	°C
Industry	Cement mills	Load shedding	0	24	Yes	No
	Mechanical wood pulp production	Load shedding	0	24	No	No
	Recycling paper processing	Load shedding	0	24	No	No
	Paper machines	Load shedding	0	24	No	No
	Calcium carbide production	Load shedding	0	24	No	No
	Air liquefaction in cryogenic rectification	Load shedding	0	24	No	No
	Cooling in food manufacturing	Load shedding	0	24	Yes	No
	Ventilation w/o process relevance	Load shedding	0	24	No	No
Tertiary	Commercial ventilation	Load shedding	0	8:00—18:00	No	No
	Commercial air conditioning and cooling	Both	6:00—18:00	12:00—20:00	No	Yes
	Commercial heating	Both	7:00—9:00	7:00—19:00	No	Yes
	Pumps in water supply	Load shedding	0	24	No	No
Residential	Cold appliances	Load shedding	0	24	Yes	No
	Wet appliances	Load shifting	24	0	Yes	No

Source: Abdisalaam et al. (2012), Gils (2014) and Olsen et al. (2014). Notes: t_{shift} is the assumed time of load shifting. t_{shed} is the assumed time of load shedding. *Season* represents that whether seasonal changes have an impact on loads. °C represents that whether temperature changes have an impact on loads. If there is no specific restriction, it is assumed that DR can be applied at all hours.

4.2 Shiftable load profiles

Load profiles, technical limits, seasons and temperatures are key for assessing the potentials of DR. The load profiles characterize the load patterns. Due to the technical limits of DR in some processes and appliances, the implementation of load shedding and shifting depends on specific time periods. In addition, seasons and temperatures cause large volatility in flexible loads and relevant potentials of DR.

4.2.1 Seasonal profiles

In the industrial sector, activity of cement production in winter is lower than that in summer. Its daytime activity is also lower than that at night time (Gils 2014). Therefore, the utilization rate of appliances in the cement industry in winter is assumed to be by 20% lower than that in summer, while the rate at day time in all seasons is two thirds of that at night time. For ventilation processes in industrial and tertiary sectors, their utilization rates at night time are assumed to be reduced by 50% of that at day time. Furthermore, due to the seasonal impact, the utilization rate of cooling purposes (cooling in manufacturing) in the industrial sector in summer is assumed to be 10% higher than that in winter. Similarly, the utilization rate of wet and cold appliances in the residential sector follows the pattern of cooling purposes in the industrial sector.

4.2.2 Temperature-dependent profiles

The energy loads of air conditioning, cooling and commercial heating are closely correlated to outside temperatures. Hourly temperature profiles for each country are collected from ECA&D (2016) to estimate the hourly loads of air conditioning, cooling and commercial heating in summer and winter seasons. For each hour, cooling degree hour is defined as the difference between mean hourly outside temperature and 15°C (base degree in Europe). If this difference is negative, the cooling degree is zero (Fan, Hyndman 2011). This difference in summer is used to examine the effect of hot temperatures on the loads of air conditioning and cooling appliances. This method can be also applied to estimate the hourly loads of heating appliances in winter. Then, the loads of air conditioning, cooling and heating appliances in summer and winter can be estimated by:

$$D^c(\mathrm{i}) = (1 + \frac{\max(0, \mathrm{T_i} - 15°\mathrm{C})}{15°\mathrm{C}})\mathrm{D_0}(\mathrm{i}), \quad (1)$$

$$D^h(\mathrm{i}) = (1 + \frac{\max(0, 15°\mathrm{C} - \mathrm{T_i})}{15°\mathrm{C}})\mathrm{D_0}(\mathrm{i})$$

where $D^c(i)$, $D^h(i)$ are the temperature-affected loads of air conditioning, cooling and commercial heating at the *i*th hour in summer and winter, D_0(i) is the original loads of air conditioning, cooling and heating at the *i*th hour, T_i is the outside temperature at the *i*th hour. $\max(0, \mathrm{T_i} - 15°\mathrm{C})$ represents that the difference between mean hourly outside temperature and 15°C is a positive value or zero at the *i*th hour.

4.3 Flexible loads in three sectors

This study estimates the potential of price-based DR on an hourly basis by price elasticities, spot prices and technical constraints of loads. More specifically, the estimation of the potentials of DR in the industrial sector depends on production capacity *C*, number of production appliances *N* and utilization rate $s_{use,i}$ at each hour. These parameters can be found in Gils (2014) and Klobasa (2007). Unlike the estimation of the potentials of DR in other papers, this study considers the effects of price changes and price elasticities (own and cross elasticities). The price elasticities of electricity in three sectors can be calculated by the model in Appendix. According to the assumption of RTP (real-time pricing) in Feuerriegel and Neumann (2014), consumers in industrial, tertiary and residential sectors face the same changes in spot prices. Thus, the calculation of the potential of DR is expressed by:

$$\mathrm{DRP^{unit}}(\mathrm{i}) = \sum_{\mathrm{j}=1}^{24} \mathrm{D_0^{unit}}(\mathrm{i})\varepsilon(\mathrm{i},\mathrm{j})(\frac{\mathrm{P}(\mathrm{j}) - \mathrm{P_0}(\mathrm{j})}{\mathrm{P_0}(\mathrm{j})}) \quad (2)$$

$$\varepsilon(\mathrm{i},\mathrm{j}) \geq 0, if\ i \neq j$$

$$\varepsilon(\mathrm{i},\mathrm{j}) \leq 0, if\ i = j$$

where $\mathrm{DRP^{unit}(i)}$ is the potential of DR (load shifting and shedding) for each process and appliance at the *i*th hour, $\mathrm{D_0^{unit}(i)}$ is the initial load at the *i*th hour, $\varepsilon(\mathrm{i},\mathrm{j})$ is the elasticity of consumer in each sector (if it is positive, it is cross elasticity; otherwise, it is own elasticity), and $P(j)$, $P_0(j)$ is the spot price and the initial spot price at the *j*th hour. Then, the initial load of each appliance can be derived from the above equation (2) as:

$$\mathrm{D_0^{unit}(i)} = \mathrm{DRP^{unit}(i)} \sum_{\mathrm{j=1}}^{24} \frac{\mathrm{P_0(j)}}{\varepsilon(\mathrm{i,j})(\mathrm{P(j)} - \mathrm{P_0(j)})} \tag{3}$$

At each hour, the retailer tries to minimize the costs. Given the fixed price, the retailer determines to minimize the total loads.

$$minC = min \sum_{i=1}^{24} \mathrm{D_0^{unit}(i)} * \mathrm{P_0(i)} \tag{4}$$

$$= min \sum_{i=1}^{24} \mathrm{DRP^{unit}(i)} * \mathrm{P_0(i)} \sum_{\mathrm{j=1}}^{24} \frac{\mathrm{P_0(j)}}{\varepsilon(\mathrm{i,j})(\mathrm{P(j)} - \mathrm{P_0(j)})}$$

Furthermore, the installed capacity is assumed to be affected by the number of operational processes and appliances, the production capacity of each appliance, the utilization rate at each hour, and the possible outrage rate. Therefore, the installed capacity as the constraint of flexible loads can be expressed by:

$$\mathrm{S_{installed}^{unit}} = \mathrm{N_{in}^{unit}} * \mathrm{C_{capa}^{unit}} * \mathrm{s_{use}^{unit}}(1 - \mathrm{s_{revision}^{unit}}) \tag{5}$$

$$\text{Or } \mathrm{S_{installed}^{unit}} = \mathrm{N_{HH}} * \mathrm{r_{unit}} * \mathrm{C_{capa}^{unit}} * \mathrm{s_{use}^{unit}}$$

where $\mathrm{S_{installed}^{unit}}$ is the installed capacity of each appliance, $\mathrm{N_{in}^{unit}}$ is the number of specific manufacturing plants in the industrial sector, or the number of total commercial enterprises in the tertiary sector[3], $\mathrm{N_{HH}}$ is the number of households, $\mathrm{r_{unit}}$ is the ownership rate of

[3] This number assumes that one manufacturing plant owns one relevant production process or appliance in the industrial sector, while in the tertiary sector one firm owns five relevant commercial electricity appliances and services (commercial cooling, ventilation, air conditioning, heating and water supply).

household appliances, C_{capa}^{unit} is the average installed capacity of relevant appliance, s_{use}^{unit} is the utilization rate, and $s_{revision}^{unit}$ is the revision rate. In this sense, the potential of price-based DR and the estimated load are subject to the installed capacity and the total load in each sector.

Therefore, under the capacity and the market clearing constraints, the complete optimization problem for a retailer in one country is given by:

$$minC = min \sum_{unit} \sum_{i=1}^{24} \mathrm{D}_0^{\mathrm{unit}}(\mathrm{i}) * P_0(i)$$

$$= min \sum_{unit} \sum_{i,j=1}^{24} \mathrm{DRP}^{\mathrm{unit}}(\mathrm{i}) * \mathrm{P}_0(\mathrm{i}) \frac{\mathrm{P}_0(\mathrm{j})}{\varepsilon(\mathrm{i,j})(\mathrm{P(j)}-\mathrm{P}_0(\mathrm{j}))} \tag{6}$$

Subject to

$$0 < \sum_{unit} \mathrm{DRP(i)} \leq \sum_{unit} S_{installed}$$

$$\sum_{unit} \sum_{i=1}^{24} \mathrm{D}_0^{\mathrm{unit}}(\mathrm{i}) * 365 = \mathrm{D_{sect}}$$

Where D_{sect} is the yearly load in each sector.

As shown, the potential of DR in the industrial sector at each hour is affected by the number of installed appliances, the production capacity, the utilization rate, the price changes, and the revision rate of appliances. Tables 2, 3, 4 and 5 summarize the assumed values of parameters in three sectors. In addition, the estimation of the flexible loads of air conditioning, cooling and commercial heating in the tertiary sector in equation (1) takes into account of the impact of outside temperatures.

Table 2: Country input for average installed capacity in each plant in the industrial sector

Process / Appliance	DE (MW)	NL (MW)	UK (MW)	DK (MW)	NO (MW)	SE (MW)	FI (MW)
Cement mills	3.077	0.747	2.472	1.8	0.459	1.076	0.034
Mechanical wood pulp production	3.01	0.027	0.073	0.02	1.72	0.201	0.213
Recycling paper processing	2.848	0.027	0.142	0.02	0. 2	0.34	0.017
Paper machines	0.714	0.131	0.065	0.02	0.24	0.96	0.194
Calcium carbide production	0.88	0.045	0.048	0.02	0.08	0.068	0.017
Air liquefaction in cryogenic rectification	2.096	0.513	0.335	1.4	3.56	0.357	0.017
Cooling in food manufacturing	2.528	1.579	2.632	0.105	0.263	0.211	0.053
Ventilation w/o process relevance	2.192	0.055	0.824	0.11	0.137	0.22	0.028

Source: Quinkertz (2002), Paulus and Borggrefe (2011), Klobasa (2007), Verein Deutscher Zementwerke (2011), Blechschmidt (2010), FAO (2015), Schleich et al.(2006), Dena (2010), Cameron (2010), Gutschi and Stigler (2008), Häring, Ahner and Belloni (2008), Radgen et al. Stadler (2006), Gils (2014) and Odyssey-Mure (2015). The method for obtaining these results is presented in the Appendix.

Table 3: Average installed capacity of appliances in each firm and household in tertiary and residential sectors

Sector	Appliance	Ave. capacity (MW)
Tertiary	Commercial ventilation	0.01
	Commercial air conditioning and cooling	0.02
	Commercial heating	0.04
	Pumps in water supply	0.04
Residential	Cold appliances	0.002
	Wet appliances	0.003

Source: Odyssey-Mure (2015), MAISY (2016) and author’s calculation. Notes: It is assumed that tertiary and residential appliances in different countries have the same average installed capacities.

Table 4: Parameters for the estimation of the potential of DR in three sectors

Sector	Appliance/Process	Utilization rate	Revision rate
Industrial	Cement mills	80%	5%
	Mechanical wood pulp production	80%	5%
	Recycling paper processing	80%	5%
	Paper machines	90%	5%
	Calcium carbide production	80%	5%
	Air liquefaction in cryogenic rectification	80%	5%
	Cooling in food manufacturing	70%	5%
	Ventilation w/o process relevance	50%	5%
Tertiary	Commercial ventilation	40%	5%
	Commercial air conditioning and cooling	40%	5%
	Commercial heating	30%	5%
	Pumps in water supply	40%	5%
Residential	Cold appliances	40%	
	Wet appliances	40%	

Source: CBS (2015), EIA (2010b, 2010a), Gils (2014), MAISY (2016) and author's calculation.

Table 5: Country input for the potentials of DR in three sectors

Variable	Germany	The Netherlands	The United Kingdom	Denmark	Norway	Sweden	Finland
N_{in}^{cm}	102	12	82	15	33	25	17
N_{in}^{mp}	1658	351	867	149	1073	1383	1689
N_{in}^{rp}	1469	521	1458	224	107	139	160
N_{in}^{pm}	597	142	337	21	18	86	86
N_{in}^{cc}	395	51	319	12	12	55	18
N_{in}^{al}	187	603	3848	114	966	74	22
N_{in}^{cf}	988	264	1081	179	92	121	95
N_{in}^{vp}	1821	376	723	384	91	239	137
N_{te} (Million)	0.7	0.2	1	0.2	0.3	0.4	0.2
N_{HH} (Million)	39.8	7.6	27.1	2.6	2.2	4.7	2.6
r_{cold}	95.04%	87.65%	78.8%	110.46%	95%	99.35%	78.5%
r_{wet}	74.43%	76.57%	69.5%	83.4%	81%	70.05%	80%
T_{smean} (°C)	16	17	16	13.5	13.2	13.2	11.7
T_{wmean} (°C)	3.8	5.8	8.8	3.5	0.3	0.7	—0.8
D_{indu} (TWh)	231.6	34.5	97.7	8.4	43.4	49.9	39.8
D_{tert} (TWh)	138.4	25.1	113.4	10.31	36.8	43	21.5
D_{resi} (TWh)	128.1	35.1	97.7	10.31	24.7	25.1	18.8

Source: ECA&D (2016), Odyssey-Mure (2015) and Osiris (2015). Notes: N_{in}: the number of industrial plants focusing on specific processes. N_{te} is the number of firms in the tertiary sector. N_{HH}: the number of households. r: the ownership rate of household appliances. cm: cement mills, mp: mechanical wood production, rp: recycling paper processing, pm: paper machines, cc: calcium carbide production, al: air liquefaction, cf: cooling in food manufacturing, vp: ventilation process, cold: cold appliances, wet: wet appliance. $T_{smean,}$ T_{wmean} are mean outside temperature in summer and winter. D_{indu}, D_{tert}, D_{resi} are industrial, tertiary and residential load data in 2014.

Table 6: Variable Definitions

Acronym	Definition
D_0	Initial loads of electricity in different sectors at each hour (MWh)
$\varepsilon_{i,j}$	Hourly price elasticities of consumers in different sectors
$P_{(j)}$	Spot price at *j*th hour(€/MWh)
$P_{0(j)}$	Initial spot price at *j*th hour (€/MWh)
D^c	Loads of specific devices affected by hot temperatures (MWh)
D^h	Loads of specific devices affected by cold temperatures (MWh)
D_{sect}	Sectoral load data in 2014 (TWh)
$DRP^{unit}{}_i$	Sum of hourly load shifting and shedding at *i*th hour for each appliance (MW)
$\mathrm{C}^{\mathrm{unit}}_{\mathrm{capa}}$	Average installed capacity for each appliance (MWh)
$\mathrm{s}^{\mathrm{unit}}_{\mathrm{use}}$	Average utilization rate for each appliance (%)
t_{shift}	Allowed time of load shifting
t_{shed}	Allowed time of load shedding
T_i	Outside temperature at the *i*th hour (°C)
T_{smean}	Mean outside temperature in summer (°C)
T_{wmean}	Mean outside temperature in winter (°C)

5. Results

To estimate the hourly potential of price-based DR, we assume that retailers deliver electricity to customers in industrial, tertiary and residential sectors. Our data relate to the price-based equations in the methodology and price data in a number of spot price exchange markets in 2014. All price data are published on an hourly basis from the year 2014 of the European Power Exchange (EPEX) (2015), the APX Power NL (2015), the APX Power UK (2015) and the Nord Pool (2015). These price data comprise all hours in weekdays. To examine the effect of time-dependency on the potentials of price-based DR, we analyze average price data in 2014 (in Figure 1).

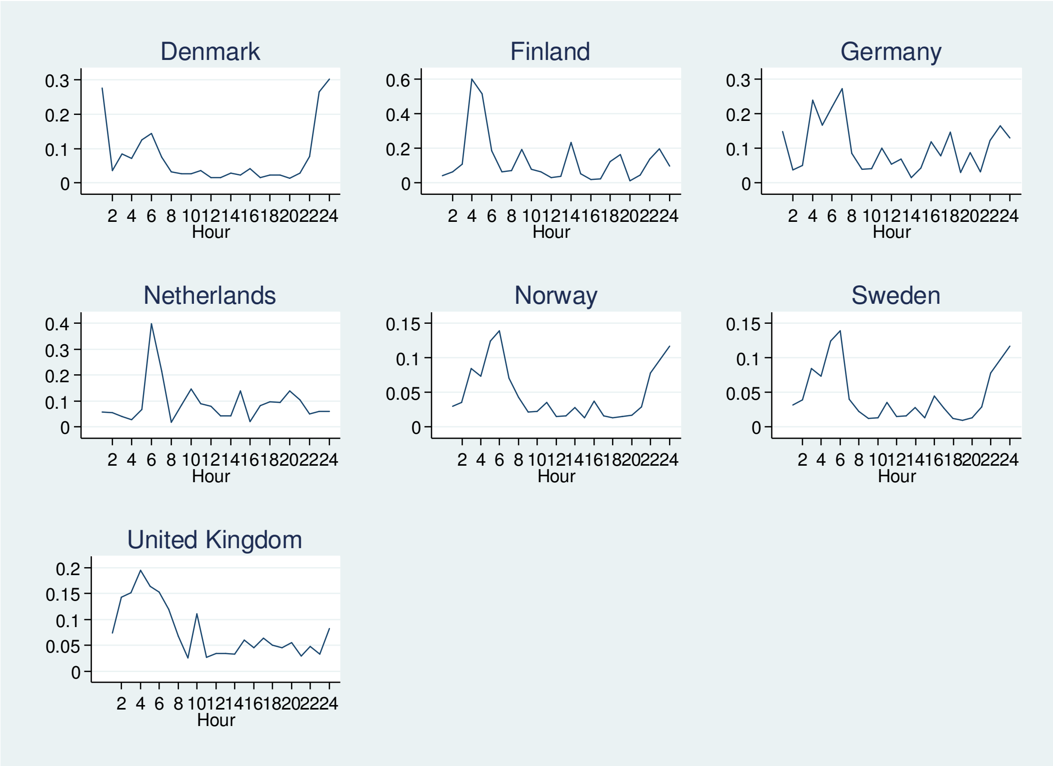

Figure 1: Average hourly spot price changes by country in 2014
Source: EPEX (2015), APX Power NL (2015), APX Power UK (2015), Nord Pool (2015) and own calculation.

Figure 1 shows the changes in average hourly spot price, which correspond to the price changes $(\frac{P_h - P_{h-1}}{P_{h-1}})$ [4] in equation (2) for a number of European countries, namely Denmark, Finland, Germany, the Netherlands, Norway, Sweden and the United Kingdom. As shown in Figure 1, price changes vary from country to country. In Scandinavia, the relatively high price changes in Denmark occur at night time, while in Finland, Norway and Sweden it is observed in the morning. The relatively high price changes in the morning also apply to Germany, the Netherlands and the United Kingdom. Notably, customers in Norway and Sweden face the similar changes in spot prices. The magnitudes of spot price changes are small, ranging from 0.05 to 0.3.

To estimate the price elasticities in European countries (the Netherlands, Germany, the United Kingdom, Finland, Denmark, Norway and Sweden), we assume that the customers in industrial, tertiary and residential sectors access electricity from local retailers with the

[4] Hereafter, the changes in spot prices refer to $(\frac{P_h - P_{h-1}}{P_{h-1}})$, unless the clear statement.

real-time prices. In addition, the averagely daily electricity consumption[5] in three sectors is given by local retailers (E. ON NL 2014, E. ON UK 2014, E. ON DE 2014, E. ON SE 2014, E. ON DK 2014, Vattenfull 2014, Fjordkraft 2014). These load profiles are presented as indexes in Figure 2. Notably, in the industrial sector, the peak loads are observed at morning time, while in the tertiary sector they are at afternoon time, and in the residential sector they are at night time.

Figure 2: Representative average daily load index by country in 2014 (based on average sectoral load in each country=100). Notes: these loads are aggregated to be hourly data.

In addition, all spot prices are based on the hourly data in 2014 of the APX Power NL (2015), the APX Power UK (2015), the European Power Exchange (EPEX) (2015), and the Nord Pool (2015). The model for calculating the price elasticities is presented in Appendix. It is assumed that the traded volumes of retailers are from the spot markets. As argued by Lijesen (2007), only 15% of total load is traded in the spot market. Therefore, all estimated

[5] These available load data are representative daily consumption on average in 2014 instead of detailed load profiles of electricity retailers.

elasticities are divided by 15%. The estimated elasticities are shown in Table 7.

Table 7: Average price elasticities at peak hours in European countries in 2014

Country	Industry	Tertiary	Households
Denmark	—0.0101 (own)	—0.0105 (own)	—0.0125 (own)
	0.0009 (cross)	0.0009 (cross)	0.0124 (cross)
Finland	—0.0053 (own)	—0.0055 (own)	—0.0097 (own)
	0.0006 (cross)	0.0007 (cross)	0.0011 (cross)
Germany	—0.0044 (own)	—0.0047 (own)	—0.0073 (own)
	0.0453 (cross)	0.0487 (cross)	0.076 (cross)
The Netherlands	—0.0021 (own)	—0.002 (own)	—0.0028 (own)
	0.0022 (cross)	0.0021 (cross)	0.003 (cross)
Norway	—0.0096 (own)	—0.0108 (own)	—0.0113 (own)
	0.0012 (cross)	0.0013 (cross)	0.0014 (cross)
Sweden	—0.0089 (own)	—0.0095 (own)	—0.0103 (own)
	0.0011 (cross)	0.0013 (cross)	0.0014 (cross)
The United Kingdom	—0.0078 (own)	—0.0078 (own)	—0.0091 (own)
	0.0012 (cross)	0.0012 (cross)	0.0014 (cross)

Notes: According to APX, the peak hours are 8:00am—20:00pm.

As shown in Table 7, the magnitudes of hourly elasticities during peak hours are ranging from 0.0006 to 0.08. These results are relatively low, compared to the elasticities presented in the literature review. Notably, the above results (around –0.002) in the Netherlands are similar to the real-time elasticity of –0.0014 in Lijesen (2007). In addition, in the United Kingdom, Denmark, Norway, Sweden and Finland, the own elasticities during peak hours are higher than the cross elasticities. By contrast, in the Netherlands and Germany, the own elasticities during peak hours are lower than the cross elasticities.

5.1 Country results

We estimate the hourly potentials of price-based DR in Denmark, Finland, Germany, the Netherlands, Norway, Sweden and the United Kingdom, using spot price data in 2014, the calculated price elasticities, and the price-based model. In particular, in Figure 3, these potentials are divided by their sectoral peak loads for comparison. As shown in Figure 3, in the industrial sector, the large share of hourly potentials in Denmark, the Netherlands, Norway, Sweden and the United Kingdom are around 0.02%—0.05% in the morning. In Germany, this figure is recorded by over 0.1% at night, while in Finland it is 0.1% in the morning.

In the tertiary sector, the large shares of the hourly potentials in Finland, Germany, the Netherlands, Norway, Sweden and the United Kingdom are around 0.01%—0.07% at 14:00—18:00. This duration corresponds to the peak business hours in the tertiary sector. Among these large shares, the largest share reaches to 0.07% in the United Kingdom in the evening. By contrast, the large share of the hourly potential in Finland is nearly 0.07% at night time.

In the residential sector, there are two peak durations for the large shares of the hourly potentials in all examined countries. The peak durations in Denmark, Finland, Norway and Sweden range from 5:00 in the morning to 18:00—19:00 in the evening, with the shares at 0.02%—0.06%. The two peak durations correspond to the peak hours in the households during working days. In addition, although the peak durations are the same in Germany, the Netherlands and the United Kingdom, the large shares of their hourly potentials are below 0.06% in the morning. On the contrary, the large share amounts to 0.13% in Finland in the morning.

As noted, the magnitudes of the hourly potentials in the residential sector are higher than those in industrial and tertiary sectors. This finding is the same as that of Beenstock, Goldin and Nabot (1999). As explained by them, residential customers are more responsive to time-varying price signals than are industrial customers. Furthermore, compared to Figure 1, the similar shape between the price changes and the changes in the shares of the hourly potentials is found in the industrial sector rather than the tertiary and residential sectors. One explanation is that the industrial sector allows both load shifting and shedding in 24 hours and observes the full price changes. However, load shifting and shedding are not 24 hours available in tertiary and residential sectors.

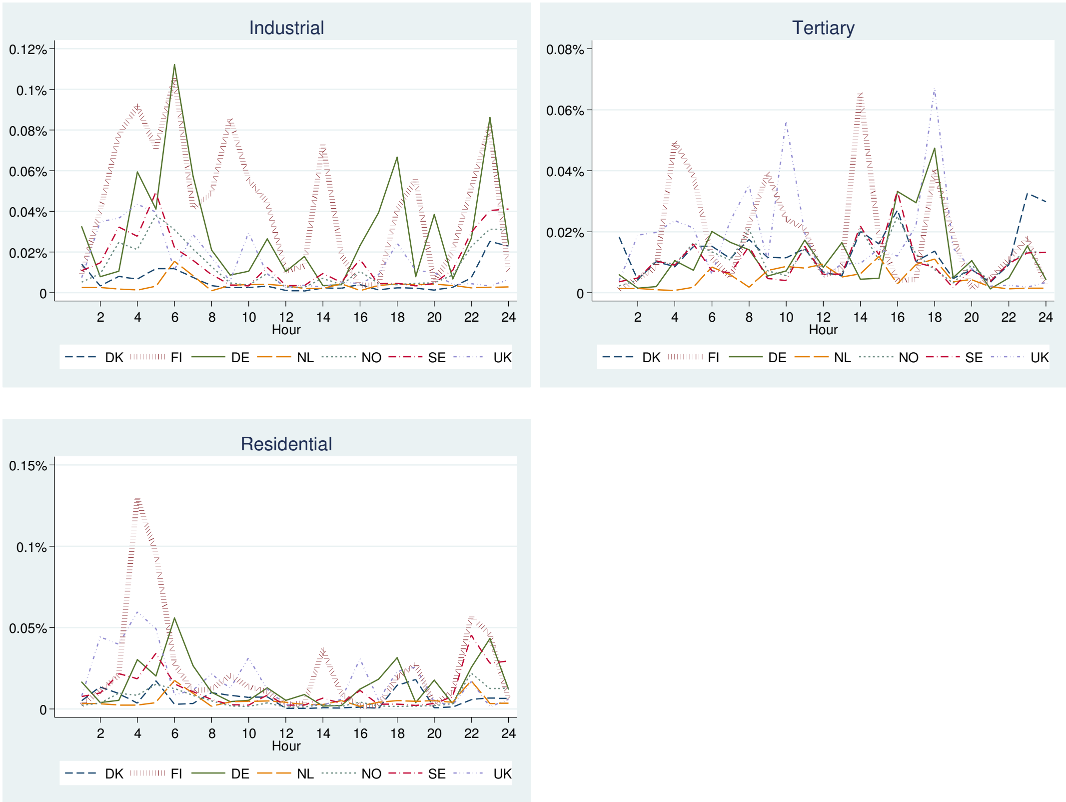

Figure 3: Share of the average hourly potential of price-based DR in peak loads by country in 2014

In short, compared to the peak loads, the hourly potentials of price-based DR in Denmark, Finland, Germany, the Netherlands, Norway, Sweden and the United Kingdom are relatively small. In addition, the dynamics of the hourly potentials in the industrial sector is in line with the changes in spot prices, while the hourly potential in the residential sector is higher than those in tertiary and industrial sector. These findings suggest that the changes in spot prices and price elasticities play important roles in determining the hourly potential of price-based DR.

5.2 Aggregated results

Figure 4 presents the results of all examined European countries at the aggregated level. As presented, in 2014, the maximum aggregated hourly potentials of price-based DR in all examined European countries added up to nearly 12MW[6] in the morning. This potential

[6] The magnitudes of the potentials are calculated based on the selected load profiles of load retailers.

accounts for 0.6% of peak loads. More specifically, in the industrial sector, the maximum aggregated hourly potential is around 5.6MW, while in the tertiary sector it is 1.6MW, and in the residential sector it is 5.2MW. Accordingly, the industrial share of maximum aggregated hourly potential in the peak loads is around 0.28%, followed by 0.08% in the tertiary sector, and 0.26% in the residential sector. The dynamics of the aggregated hourly potentials are similar to those in the country results. The relatively small hourly potential of price-based DR is observed at the aggregated level. Notably, the large proportion of the potentials of price-based DR arises at early morning and late night.

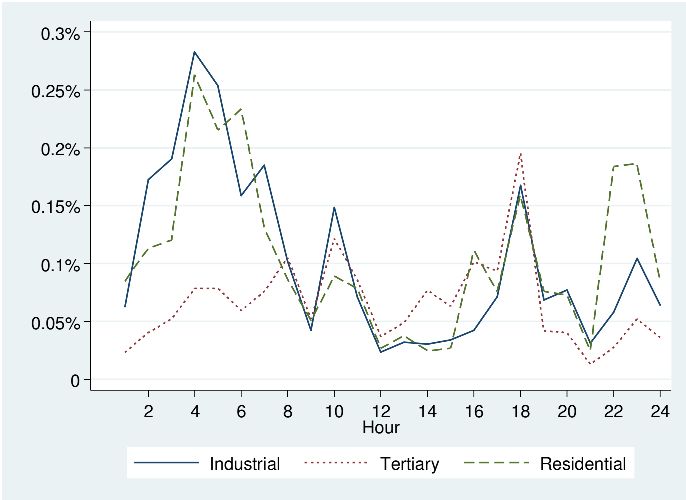

Figure 4: Average aggregated hourly potentials of price-based DR in all examined countries for working days in 2014

The share of the hourly potential of price-based DR is distributed unevenly over different sectors, countries and appliances. The residential share in country's average hourly potential ranges from 68% in the Netherlands to 93% in Denmark, whereas the tertiary share varies from 5% in Germany to 25% in the Netherlands, and the industrial share from 0.5% in Denmark to 13% in the United Kingdom (in Figure 5). Indeed, the residential sector dominates more than two thirds of the overall potential in all examined countries. The tertiary sector in the Netherlands and the industrial sector in the United Kingdom gain the relatively large shares. Moreover, the large share of the potential in the industrial sector is found in the appliances of cooling in food manufacturing (40%) and air liquefaction (25%), while in the tertiary sector, 48% of the potential is contributed by pumps in water supply, and 11% by commercial air conditioning and cooling, and commercial heating (in Figure 6). In the residential sector, most of the potential (99%) is centered in the cold appliances.

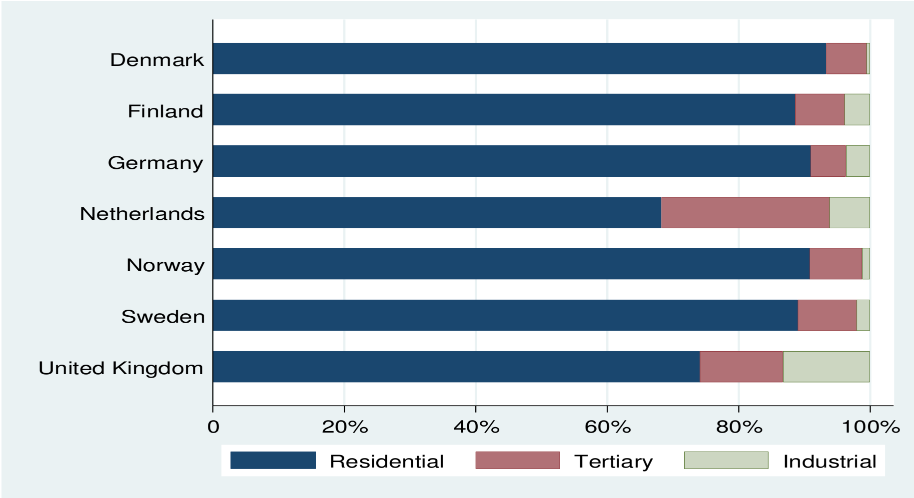

Figure 5: Sectoral shares in the average hourly potential of price-based DR

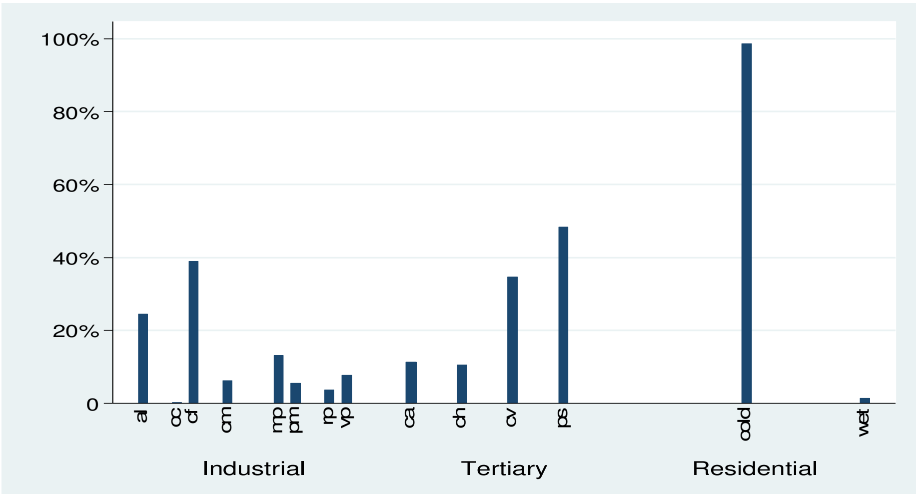

Figure 6: Appliance shares in the average sectoral potential of price-based DR
Notes: cm: cement mills, mp: mechanical wood production, rp: recycling paper processing, pm: paper machines, cc: calcium carbide production, al: air liquefaction, cf: cooling in food manufacturing, vp: ventilation process, cv: commercial ventilation, ca: commercial air conditioning and cooling, ch: commercial heating, ps: pumps in water supply, cold: cold appliances, wet: wet appliances.

Figures 7 illustrates the average hourly potentials of six representative appliances (air liquefaction, cooling in food manufacturing, commercial air conditioning and cooling, commercial heating, pumps in water supply and cold appliances) in February, May and

August. These months stand for winter, spring and summer[7]. Therefore, Figure 7 indicates the impacts of seasonal changes and outside temperatures on the hourly potentials. As illustrated, the hourly potentials of all selected appliances display a similar pattern. The maximum hourly potential of cold appliances changes from 0.1MW at night time in February, 0.2MW at morning time in May to 0.3MW at both morning and night time in August. Except for the cold appliances, the maximum potential in February is found at 0.14MW in the commercial heating at morning time, while in May is 0.3MW in the pumps in water supply at morning time, and in August 0.25MW in the air conditioning and cooling in the afternoon. Differences between seasons are primarily associated with the fraction of commercial air conditioning and cooling, and commercial heating. Furthermore, the potential of air liquefaction is less volatile than that of other appliances, implying that it is less affected by seasons and outside temperatures. In contrast, the potentials of commercial air conditioning and cooling, and commercial heating are high in summer and winter, suggesting that they are significantly influenced by outside temperatures and seasons. Compared to the potential in May, the relatively high potentials of commercial air conditioning and cooling, and commercial heating are observed at business hours in August and February.

[7] The price data in February, May and August are examined to calculate the relevant hourly potentials. Due to the similar load changes in spring and autumn, there is no analysis for the hourly potential in autumn.

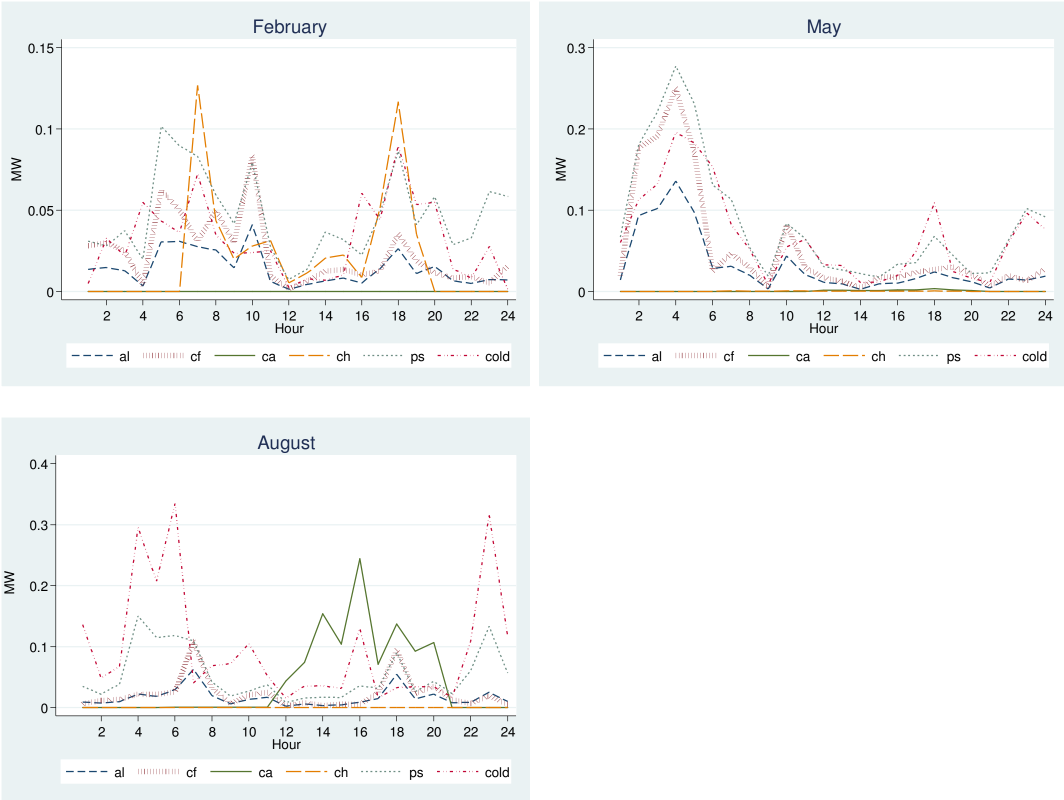

Figure 7: Average hourly potential of price-based DR by appliances in February, May and August, 2014

Notes: al: air liquefaction, cf: cooling in food manufacturing, ca: commercial air conditioning, ch: commercial heating, ps: pumps in water supply, cold: cold appliances.

Table 8 demonstrates the sensitivity of the results to 10% increases in price elasticities, volatility of spot prices and installed capacities. Panels A and B of Table 8 shows that a 10% increase in price elasticities and volatility of spot prices results in a rise in the potentials of price-based DR with a range of 10%—20%. Panel C of Table 8 shows that changes in installed capacity have small impacts on the potentials of price-based DR, namely an increase up to 0.09%. Accordingly, in Table 8, after an increase in price elasticities, volatility of spot prices and installed capacities, the cost of a retailer is not significantly affected. The sensitivity analysis indicates that the potential of price-based DR significantly depends on price elasticities and price changes, while the potential is robust to the assumption of installed capacity. Similarly, the cost of a retailer is robust to price elasticities, volatility of spot prices and installed capacities. In addition, Table 9 suggests that only a minor change in the potential of price-based DR is observed when using a load-based estimation model.

Table 8: Sensitivity analysis of changes in price elasticities, volatility of spot prices and installed capacities

Panel A: 10% increase in price elasticities				
Country	Daily potential of price-based DR (MW)	Change (%)	Daily cost	Change (%)
Denmark	4	20.79	€2.8×10^6	—0.06
Finland	6	15.16	€5.0×10^6	—0.01
Germany	38	8.41	€2.8×10^7	—0.02
The Netherlands	5	24.78	€4.0×10^6	—0.01
Norway	6	15.79	€9.5×10^6	—0.03
Sweden	9	6.34	€9.1×10^6	—0.04
The United Kingdom	37	15.93	€1.1×10^7	—0.04
Panel B: 10% increase in volatility of spot prices				
Country	Daily potential of price-based DR (MW)	Change (%)	Daily cost	Change (%)
Denmark	4	20.79	€2.8×10^6	—0.06
Finland	6	15.16	€5.0×10^6	—0.01
Germany	38	8.41	€2.8×10^7	—0.02
The Netherlands	5	24.78	€4.0×10^6	—0.01
Norway	6	15.79	€9.5×10^6	—0.03
Sweden	9	6.34	€9.1×10^6	—0.04
The United Kingdom	37	15.93	€1.1×10^7	—0.04
Panel C: 10% increase in installed capacities				
Country	Daily potential of price-based DR (MW)	Change (%)	Daily cost	Change (%)
Denmark	3	0.02	€2.8×10^6	—0.09
Finland	5	0.03	€5.0×10^6	—0.02
Germany	35	0.03	€2.8×10^7	—0.04
The Netherlands	4	0.02	€4.0×10^6	—0.03
Norway	5	0.09	€9.5×10^6	—0.01
Sweden	8	0.07	€9.1×10^6	—0.02
The United Kingdom	32	0.06	€1.1×10^7	—0.07

Notes: The results of potentials are the aggregated daily potentials under the assumption changes.

Table 9: Comparison of results between price-based and load-based models

Country	Potential of price-based model (MWh)	Potential of load-based model (MWh)	Change (%)
Denmark	3.1	3.3	6.5
Finland	5.2	4.9	—6.8
Germany	35.4	37.2	5.1
The Netherlands	4.1	4.3	4.9
Norway	5.2	5.6	7.7
Sweden	8.1	7.7	—4.9
The United Kingdom	32.4	31.5	—2.8

Notes: The potential of load based model is calculated by multiplying the representative retailers' loads (shown in Figure 2) by the available percentage of price-based DR in loads (shown in Figure 3).

In summary, the overall hourly potential for all examined countries is relatively small. The large residential, tertiary and industrial shares in the hourly potentials are observed in Denmark, the Netherlands and the United Kingdom. In contrast to most appliances, the hourly potentials in commercial air conditioning and cooling, and commercial heating are significantly affected by outside temperatures and seasons.

6. Conclusions

This study estimates the hourly potential of price-based DR for the residential users in a number of European countries. As estimated, the maximum aggregated hourly potential of price-based DR in all examined European countries in 2014 represents 0.6% of peak loads at morning time. In the industrial sector, the share of maximum hourly potential in the peak loads is contributed by 0.28%, 0.08% in the tertiary sector, and 0.26% in the residential sector. The potentials of price-based DR in the residential sector are not significantly higher than those in other sectors. These results are lower than the DR potentials in all European countries by Gils (2014) and the potential of price-based DR in the U.S. by Cappers, Goldman and Kathan (2010) accounting for 6% of peak loads. As noted, Gils (2014) calculates both price-based and incentive-based DR using load-based models. Possible reasons are the low traded volumes, the relatively low price elasticities and the small price changes in the wholesale market.

This relatively small potential of price-based DR is aligned with the relatively small available percentage of price-based DR in total DR, the small price elasticities and the small price changes in the wholesale market. Firstly, as surveyed by Cappers, Goldman and Kathan (2010), in 2008 the percentage of US customers enrolled in existing incentive-based DR in total DR reached 93%. The price-based DR alone is not capable of providing large load adjustment. Secondly, in this study, the magnitudes of hourly elasticities are in the range of 0.0006 to 0.08. The small hourly price elasticities are closely related to the potentials of price-based DR. As argued by Lijesen (2007), the small hourly elasticities lie in the low traded volumes in the wholesale market. Large users have contracted a fixed amount of electricity (approximately 85%) before the transactions in the wholesale market. Thirdly, the price spikes in the wholesale market are too small to generate sufficient incentives for curtailing loads. As shown in Figure 1, for the examined countries, the small spot price spikes are observed from 0.05 to 0.3.

In addition, the estimation results show that the large share of the hourly potential is characterized by the cooling in food manufacturing in the industrial sector, the pumps in water supply in the tertiary sector, and the cold appliances in the residential sector. The potentials in both commercial air conditioning and cooling, and commercial heating are significantly influenced by seasons and outside temperatures.

From this study follows a number of policy implications for balancing electricity and reducing costs of end-users. Compared to peak loads, the estimated relatively low hourly potential suggests that the price-based DR alone has a limited effect on balancing electricity in case of increasing supply of intermittent renewable energy sources. Evidence from the aggregated and country results show that rises in price elasticities and volatility of spot prices can increase the potential of price-based DR, reduce its peak loads and then reduce the costs of end-users. However, as suggested by Lijesen (2007), low hourly price elasticities imply that government policies to foster DR may be not effective because customers may not be willing to react to spot prices at all. In addition, policies of load management should primarily focus on the appliances of cooling in food manufacturing, pumps in water supply and fridges which account for large potential of price-based DR.

Finally, it should be noted that the relatively small results of price elasticities and hourly potentials of price-based DR are conditional on the assumption that they are subject to the price changes in the spot market. These price changes are influenced by different aggregated behaviors of all market participants (for example, fuel prices, network congestion and price speculation). Thus, the magnitudes of estimated results of price elasticities and potentials are related to those aggregated behaviors.

Appendix:

A.1. Abbreviations

APX	Dutch Power Spot Exchange Market
CPP	Critical Peak Pricing
DE	Germany
DK	Denmark
DR	Demand Response
EPEX	European Power Exchange
FI	Finland
ISO	Independent System Operator
MWh	Megawatt-hour
NL	Netherlands
NO	Norway
RTP	Real Time Pricing
SE	Sweden
TOU	Time of Use
UK	United Kingdom

A.2. Installed capacity

The installed capacity for processes and appliances in the industrial sector is estimated by the method in Gils (2014) and relevant data from existing literature (listed in Table 2). The method in Gils (2014) is as follows:

$$P_{installed,i} = \frac{C_i * W_i^{spec}}{N_{hour} * (1 - s_{revision,i})}$$

where $P_{installed,i}$ is the installed capacity, C_i is the production capacity of each appliance, W_i^{spec} is the specific electricity loads of each appliance, N_{hour} is the total number of hours of the year and $s_{revision,i}$ is the rate of revision outages.

A. 3. Price elasticities

The price elasticity is defined as the demand sensitivity with respect to the price:

$$\varepsilon(i,j) = \frac{P_0(j)}{d_0(i)} \frac{\partial d(i)}{\partial P(j)}$$

$$\varepsilon(i,j) \geq 0, \text{if } i \neq j$$

$$\varepsilon(i,j) \leq 0, \text{if } i = j$$

where $\varepsilon(i,j)$ is the price elasticity (own elasticity is negative $\varepsilon(i,j) \leq 0$ while cross elasticity is positive $\varepsilon(i,j) \geq 0$). $P_0(j), d_0(i)$ are the initial price and load at time *j*, and $P(j), d(i)$ is the price and load at time *j*.

If data regarding the loads of consumers in each sector is available in specific country, the price elasticities can be calculated using the method in Kirschen et al.(2000).

Kirschen et al. (2000) assume that if a consumer under inelastic demand is charged with a high price for a product, there is no reduction in consumer's responsive consumption. Thus, over 24 hours, the following relation holds (Kirschen et al. 2000):

$$\sum_{j=1}^{24} \varepsilon(i,j) \leq 0$$

And the above equation subject to the constraint that:

$$\partial d(i) = d_0(i) \sum_{j=1}^{24} \varepsilon(i,j) \frac{\partial P(j)}{P_0(j)}$$

With the above function and constraint, the 24-hour price elasticities can be derived.

References:

Abdisalaam, A., Lampropoulos, I., Frunt, J., Verbong, G.P. & Kling, W.L. 2012, "Assessing the economic benefits of flexible residential load participation in the Dutch day-ahead auction and balancing market", *European Energy Market (EEM),* , pp. 1-8.

Al-Faris, A.R.F. 2002, "The demand for electricity in the GCC countries", *Energy Policy,* vol. 30, no. 2, pp. 117-124.

APX Power NL 2015, *Dutch Power Spot Exchange: Spot Prices*, Dutch Power Spot Exchange, Amsterdam.

APX Power UK 2015, *British Power Spot Exchange: Spot Prices*, British Power Spot Exchange, London.

Beenstock, M., Goldin, E. & Nabot, D. 1999, "The demand for electricity in Israel", *Energy Economics,* vol. 21, no. 2, pp. 168-183.

Blechschmidt, J. 2010, *Taschenbuch der Papiertechnik,* München: Fachbuchverlag Leipzig im Carl-Hanser-Verlag.

Cameron, W. (ed) 2010, *Kirk-Othmer encyclopedia of chemical technology*, John Wiley & Sons Ltd., New York.

Cappers, P., Goldman, C. & Kathan, D. 2010, "Demand response in U.S. electricity markets: Empirical evidence", *Energy,* vol. 35, no. 4, pp. 1526-1535.

CBS 2015, *Manufacturing and Energy*, National Dutch Bureau of Statistics, Den Haag, The Netherlands.

Darby, S.J. & McKenna, E. 2012, "Social implications of residential demand response in cool temperate climates", *Energy Policy,* vol. 49, pp. 759-769.

Dena 2010, *dena Grid Study II. Integration of Renewable Energy Sources in the German Power Supply System from 2015–2020 with an Outlook to 2025*, German Energy Agency, Berlin.

E. ON DE 2014, *Average electricity load curves by representative customers in industrial, tertiary and residential sectors in Germany*, E. ON DE, Germany.

E. ON DK 2014, *Average electricity load curves by representative customers in industrial, tertiary and residential sectors in Denmark*, E. ON DK, Denmark.

E. ON NL 2014, *Average electricity load curves by representative customers in industrial, tertiary and residential sectors in the Netherlands*, E. ON NL, The Netherlands.

E. ON SE 2014, *Average electricity load curves by representative customers in industrial, tertiary and residential sectors in Sweden*, E. ON SE, Sweden.

E. ON UK 2014, *Average electricity load curves by representative customers in industrial, tertiary and residential sectors in United Kingdom*, E. ON UK, United Kingdom.

ECA&D 2016, *European Climate Assessment & Dataset*, Royal Netherlands Meteorological Institute (KNMI), De Bilt.

EIA 2010a, *Commercial Buildings Energy Consumption Survey (CBECS)*, Energy Information Administration, U.S. Department of Energy, Washington DC.

EIA 2010b, *Manufacturing Energy Consumption Survey (MECS)*, Energy Information Administration, U.S. Department of Energy, Washington DC.

EPEX 2015, *European Power Exchange: Spot Prices*, European Power Exchange, Paris.

European Commission 2014, *A policy framework for climate and energy in the period from 2020 to 2030*, European Commission, Brussels.

Fan, S. & Hyndman, R.J. 2011, "The price elasticity of electricity demand in South Australia", *Energy Policy,* vol. 39, no. 6, pp. 3709-3719.

Feuerriegel, S. & Neumann, D. 2014, "Measuring the financial impact of demand response for electricity retailers", *Energy Policy,* vol. 65, no. 6, pp. 359-368.

Filippini, M. & Pachauri, S. 2004, "Elasticities of electricity demand in urban Indian households", *Energy Policy,* vol. 32, no. 3, pp. 429-436.

Fjordkraft 2014, *Average electricity load curves by representative customers in industrial, tertiary and residential sectors in Norway*, Fjordkraft, Norway.

Gils, H.C. 2014, "Assessment of the theoretical demand response potential in Europe", *Energy,* vol. 67, pp. 1-18.

Gutschi, C. & Stigler, H. 2008, *Potenziale und Hemmnisse für Power Demand Side Management in Österreich*, Proceedings of the 10th Symposium Energy Innovation, Graz, Austria.

Häring, H., Ahner, C. & Belloni, A. 2008, *Industrial gases processing,* Wiley Online Library, Munchen.

Holtedahl, P. & Joutz, F.L. 2004, "Residential electricity demand in Taiwan", *Energy Economics,* vol. 26, no. 2, pp. 201-224.

Hurley, D., Peterson, P. & Whited, M. 2013, *Demand response as a power system resource*, Synapse Energy Economics Inc., Brussels.

Kirschen, D.S., Strbac, G., Cumperayot, P. & de Paiva Mendes, D. 2000, "Factoring the elasticity of demand in electricity prices", *Power Systems, IEEE Transactions on,* vol. 15, no. 2, pp. 612-617.

Klobasa, M. 2007, *Dynamische Simulation eines Lastmanagements und Integration von Windenergie in ein Elektrizitätsnetz auf Landesebene unter regelungstechnischen und Kostengesichtspunkten*, ETH Zürich.

Lijesen, M.G. 2007, "The real-time price elasticity of electricity", *Energy Economics,* vol. 29, no. 2, pp. 249-258.

MAISY 2016, *MAISY Utility Customer Databases*, Jackson Associates, Orlando.

Müller, T. 2015, "Demand Response–Temporal Availability and Actual Use for the Electricity System", 38th International IAEE Conference, Antalya, May 2015, pp. 1.

Nord Pool 2015, *Nord Pool Spot System Price*, Nord Pool, Lysaker.

Odyssey-Mure 2015, *Energy Efficiency Trends and Policies*, Odyssey-Mure, France.

Olsen, D.J., Nance Matson, Michael D. Sohn, Cody Rose, Junqiao Dudley, Sasank Goli & Sila Kiliccote 2014, *Grid Integration of Aggregated Demand Response, Part 1: Load Availability Profiles and Constraints for the Western Interconnection*, U.S. Department of Energy, California.

Osiris 2015, *Information on listed companies across the globe*, Osiris, Brussels.

Paulus, M. & Borggrefe, F. 2011, "The potential of demand-side management in energy-intensive industries for electricity markets in Germany", *Applied Energy,* vol. 88, no. 2, pp. 432-441.

Quinkertz, R. 2002, *Optimierung der Energienutzung bei der Aluminiumherstellung,* .

Schleich, J., Nathani, C., Meyer, B. & Lutz, C. 2006, *Endogenous technological change and CO2-Emissions*, Fraunhofer IRB Verlag, München.

SEDC 2015, *Mapping Demand Response in Europe Today*, Smart Energy Demand Coalition, Brussels.

Stadler, I. 2006, *Demand response: nichtelektrische Speicher für Elektrizitätsversorgungssysteme mit hohem Anteil erneuerbarer Energien*, University of Kassel.

Torriti, J., Hassan, M.G. & Leach, M. 2010, "Demand response experience in Europe:

Policies, programmes and implementation", *Energy,* vol. 35, no. 4, pp. 1575-1583.

United Nations Food and Agriculture Organization (FAO) 2015, . Available: http:// data.un.org.

USDE 2006, *Benefits of demand response in electricity markets and recommendations for achieving them*, U.S. Department of Energy, Washington DC.

Vattenfull 2014, *Average electricity load curves by representative customers in industrial, tertiary and residential sectors in Finland*, Vattenfull, Finland.

Verein Deutscher Zementwerke 2011, *Umweltdaten der deutschen Zementindustrie 2010*, Verein Deutscher Zementwerke, Düsseldorf.

List of research reports

12001-HRM&OB: Veltrop, D.B., C.L.M. Hermes, T.J.B.M. Postma and J. de Haan, A Tale of Two Factions: Exploring the Relationship between Factional Faultlines and Conflict Management in Pension Fund Boards

12002-EEF: Angelini, V. and J.O. Mierau, Social and Economic Aspects of Childhood Health: Evidence from Western-Europe

12003-Other: Valkenhoef, G.H.M. van, T. Tervonen, E.O. de Brock and H. Hillege, Clinical trials information in drug development and regulation: existing systems and standards

12004-EEF: Toolsema, L.A. and M.A. Allers, Welfare financing: Grant allocation and efficiency

12005-EEF: Boonman, T.M., J.P.A.M. Jacobs and G.H. Kuper, The Global Financial Crisis and currency crises in Latin America

12006-EEF: Kuper, G.H. and E. Sterken, Participation and Performance at the London 2012 Olympics

12007-Other: Zhao, J., G.H.M. van Valkenhoef, E.O. de Brock and H. Hillege, ADDIS: an automated way to do network meta-analysis

12008-GEM: Hoorn, A.A.J. van, Individualism and the cultural roots of management practices

12009-EEF: Dungey, M., J.P.A.M. Jacobs, J. Tian and S. van Norden, On trend-cycle decomposition and data revision

12010-EEF: Jong-A-Pin, R., J-E. Sturm and J. de Haan, Using real-time data to test for political budget cycles

12011-EEF: Samarina, A., Monetary targeting and financial system characteristics: An empirical analysis

12012-EEF: Alessie, R., V. Angelini and P. van Santen, Pension wealth and household savings in Europe: Evidence from SHARELIFE

13001-EEF: Kuper, G.H. and M. Mulder, Cross-border infrastructure constraints, regulatory measures and economic integration of the Dutch – German gas market

13002-EEF: Klein Goldewijk, G.M. and J.P.A.M. Jacobs, The relation between stature and long bone length in the Roman Empire

13003-EEF: Mulder, M. and L. Schoonbeek, Decomposing changes in competition in the Dutch electricity market through the Residual Supply Index

13004-EEF: Kuper, G.H. and M. Mulder, Cross-border constraints, institutional changes and integration of the Dutch – German gas market

13005-EEF: Wiese, R., Do political or economic factors drive healthcare financing privatisations? Empirical evidence from OECD countries

13006-EEF: Elhorst, J.P., P. Heijnen, A. Samarina and J.P.A.M. Jacobs, State transfers at different moments in time: A spatial probit approach

13007-EEF: Mierau, J.O., The activity and lethality of militant groups: Ideology, capacity, and environment

13008-EEF: Dijkstra, P.T., M.A. Haan and M. Mulder, The effect of industry structure and yardstick design on strategic behavior with yardstick competition: an experimental study

13009-GEM: Hoorn, A.A.J. van, Values of financial services professionals and the global financial crisis as a crisis of ethics

13010-EEF: Boonman, T.M., Sovereign defaults, business cycles and economic growth in Latin America, 1870-2012

13011-EEF: He, X., J.P.A.M Jacobs, G.H. Kuper and J.E. Ligthart, On the impact of the global financial crisis on the euro area

13012-GEM: Hoorn, A.A.J. van, Generational shifts in managerial values and the coming of a global business culture

13013-EEF: Samarina, A. and J.E. Sturm, Factors leading to inflation targeting – The impact of adoption

13014-EEF: Allers, M.A. and E. Merkus, Soft budget constraint but no moral hazard? The Dutch local government bailout puzzle

13015-GEM: Hoorn, A.A.J. van, Trust and management: Explaining cross-national differences in work autonomy

13016-EEF: Boonman, T.M., J.P.A.M. Jacobs and G.H. Kuper, Sovereign debt crises in Latin America: A market pressure approach

13017-GEM: Oosterhaven, J., M.C. Bouwmeester and M. Nozaki, The impact of production and infrastructure shocks: A non-linear input-output programming approach, tested on an hypothetical economy

13018-EEF: Cavapozzi, D., W. Han and R. Miniaci, Alternative weighting structures for multidimensional poverty assessment

14001-OPERA: Germs, R. and N.D. van Foreest, Optimal control of production-inventory systems with constant and compound poisson demand

14002-EEF: Bao, T. and J. Duffy, Adaptive vs. eductive learning: Theory and evidence

14003-OPERA: Syntetos, A.A. and R.H. Teunter, On the calculation of safety stocks

14004-EEF: Bouwmeester, M.C., J. Oosterhaven and J.M. Rueda-Cantuche, Measuring the EU value added embodied in EU foreign exports by consolidating 27 national supply and use tables for 2000-2007

14005-OPERA: Prak, D.R.J., R.H. Teunter and J. Riezebos, Periodic review and continuous ordering

14006-EEF: Reijnders, L.S.M., The college gender gap reversal: Insights from a life-cycle perspective

14007-EEF: Reijnders, L.S.M., Child care subsidies with endogenous education and fertility

14008-EEF: Otter, P.W., J.P.A.M. Jacobs and A.H.J. den Reijer, A criterion for the number of factors in a data-rich environment

14009-EEF: Mierau, J.O. and E. Suari Andreu, Fiscal rules and government size in the European Union

14010-EEF: Dijkstra, P.T., M.A. Haan and M. Mulder, Industry structure and collusion with uniform yardstick competition: theory and experiments

14011-EEF: Huizingh, E. and M. Mulder, Effectiveness of regulatory interventions on firm behavior: a randomized field experiment with e-commerce firms

14012-GEM: Bressand, A., Proving the old spell wrong: New African hydrocarbon producers and the 'resource curse'

14013-EEF: Dijkstra P.T., Price leadership and unequal market sharing: Collusion in experimental markets

14014-EEF: Angelini, V., M. Bertoni, and L. Corazzini, Unpacking the determinants of life satisfaction: A survey experiment

14015-EEF: Heijdra, B.J., J.O. Mierau, and T. Trimborn, Stimulating annuity markets

14016-GEM: Bezemer, D., M. Grydaki, and L. Zhang, Is financial development bad for growth?

14017-EEF: De Cao, E. and C. Lutz, Sensitive survey questions: measuring attitudes regarding female circumcision through a list experiment

14018-EEF: De Cao, E., The height production function from birth to maturity

14019-EEF: Allers, M.A. and J.B. Geertsema, The effects of local government amalgamation on public spending and service levels. Evidence from 15 years of municipal boundary reform

14020-EEF: Kuper, G.H. and J.H. Veurink, Central bank independence and political pressure in the Greenspan era

14021-GEM: Samarina, A. and D. Bezemer, Do Capital Flows Change Domestic Credit Allocation?

14022-EEF: Soetevent, A.R. and L. Zhou, Loss Modification Incentives for Insurers Under ExpectedUtility and Loss Aversion

14023-EEF: Allers, M.A. and W. Vermeulen, Fiscal Equalization, Capitalization and the Flypaper Effect.

14024-GEM: Hoorn, A.A.J. van, Trust, Workplace Organization, and Comparative Economic Development.

14025-GEM: Bezemer, D., and L. Zhang, From Boom to Bust in de Credit Cycle: The Role of Mortgage Credit.

14026-GEM: Zhang, L., and D. Bezemer, How the Credit Cycle Affects Growth: The Role of Bank Balance Sheets.

14027-EEF: Bružikas, T., and A.R. Soetevent, Detailed Data and Changes in Market Structure: The Move to Unmanned Gasoline Service Stations.

14028-EEF: Bouwmeester, M.C., and B. Scholtens, Cross-border Spillovers from European Gas Infrastructure Investments.

14029-EEF: Lestano, and G.H. Kuper, Correlation Dynamics in East Asian Financial Markets.

14030-GEM: Bezemer, D.J., and M. Grydaki, Nonfinancial Sectors Debt and the U.S. Great Moderation.

14031-EEF: Hermes, N., and R. Lensink, Financial Liberalization and Capital Flight: Evidence from the African Continent.

14032-OPERA: Blok, C. de, A. Seepma, I. Roukema, D.P. van Donk, B. Keulen, and R. Otte, Digitalisering in Strafrechtketens: Ervaringen in Denemarken, Engeland, Oostenrijk en Estland vanuit een Supply Chain Perspectief.

14033-OPERA: Olde Keizer, M.C.A., and R.H. Teunter, Opportunistic condition-based maintenance and aperiodic inspections for a two-unit series system.

14034-EEF: Kuper, G.H., G. Sierksma, and F.C.R. Spieksma, Using Tennis Rankings to Predict Performance in Upcoming Tournaments

15001-EEF: Bao, T., X. Tian, X. Yu, Dictator Game with Indivisibility of Money

15002-GEM: Chen, Q., E. Dietzenbacher, and B. Los, The Effects of Ageing and Urbanization on China’s Future Population and Labor Force

15003-EEF: Allers, M., B. van Ommeren, and B. Geertsema, Does intermunicipal cooperation create inefficiency? A comparison of interest rates paid by intermunicipal organizations, amalgamated municipalities and not recently amalgamated municipalities

15004-EEF: Dijkstra, P.T., M.A. Haan, and M. Mulder, Design of Yardstick Competition and Consumer Prices: Experimental Evidence

15005-EEF: Dijkstra, P.T., Price Leadership and Unequal Market Sharing: Collusion in Experimental Markets

15006-EEF: Anufriev, M., T. Bao, A. Sutin, and J. Tuinstra, Fee Structure, Return Chasing and Mutual Fund Choice: An Experiment

15007-EEF: Lamers, M., Depositor Discipline and Bank Failures in Local Markets During the Financial Crisis

15008-EEF: Oosterhaven, J., On de Doubtful Usability of the Inoperability IO Model

15009-GEM: Zhang, L. and D. Bezemer, A Global House of Debt Effect? Mortgages and Post-Crisis Recessions in Fifty Economies

15010-I&O: Hooghiemstra, R., N. Hermes, L. Oxelheim, and T. Randøy, The Impact of Board Internationalization on Earnings Management

15011-EEF: Haan, M.A., and W.H. Siekman, Winning Back the Unfaithful while Exploiting the Loyal: Retention Offers and Heterogeneous Switching Costs

15012-EEF: Haan, M.A., J.L. Moraga-González, and V. Petrikaite, Price and Match-Value Advertising with Directed Consumer Search

15013-EEF: Wiese, R., and S. Eriksen, Do Healthcare Financing Privatisations Curb Total Healthcare Expenditures? Evidence from OECD Countries

15014-EEF: Siekman, W.H., Directed Consumer Search

15015-GEM: Hoorn, A.A.J. van, Organizational Culture in the Financial Sector: Evidence from a Cross-Industry Analysis of Employee Personal Values and Career Success

15016-EEF: Te Bao, and C. Hommes, When Speculators Meet Constructors: Positive and Negative Feedback in Experimental Housing Markets

15017-EEF: Te Bao, and Xiaohua Yu, Memory and Discounting: Theory and Evidence

15018-EEF: Suari-Andreu, E., The Effect of House Price Changes on Household Saving Behaviour: A Theoretical and Empirical Study of the Dutch Case

15019-EEF: Bijlsma, M., J. Boone, and G. Zwart, Community Rating in Health Insurance: Trade-off between Coverage and Selection

15020-EEF: Mulder, M., and B. Scholtens, A Plant-level Analysis of the Spill-over Effects of the German *Energiewende*

15021-GEM: Samarina, A., L. Zhang, and D. Bezemer, Mortgages and Credit Cycle Divergence in Eurozone Economies

16001-GEM: Hoorn, A. van, How Are Migrant Employees Manages? An Integrated Analysis

16002-EEF: Soetevent, A.R., Te Bao, A.L. Schippers, A Commercial Gift for Charity

16003-GEM: Bouwmeerster, M.C., and J. Oosterhaven, Economic Impacts of Natural Gas Flow Disruptions

16004-MARK: Holtrop, N., J.E. Wieringa, M.J. Gijsenberg, and P. Stern, Competitive Reactions to Personal Selling: The Difference between Strategic and Tactical Actions

16005-EEF: Plantinga, A. and B. Scholtens, The Financial Impact of Divestment from Fossil Fuels

16006-GEM: Hoorn, A. van, Trust and Signals in Workplace Organization: Evidence from Job Autonomy Differentials between Immigrant Groups

16007-EEF: Willems, B. and G. Zwart, Regulatory Holidays and Optimal Network Expansion

16008-GEF: Hoorn, A. van, Reliability and Validity of the Happiness Approach to Measuring Preferences

16009-EEF: Hinloopen, J., and A.R. Soetevent, (Non-)Insurance Markets, Loss Size Manipulation and Competition: Experimental Evidence

16010-EEF: Bekker, P.A., A Generalized Dynamic Arbitrage Free Yield Model

16011-EEF: Mierau, J.A., and M. Mink, A Descriptive Model of Banking and Aggregate Demand

16012-EEF: Mulder, M. and B. Willems, Competition in Retail Electricity Markets: An Assessment of Ten Year Dutch Experience

16013-GEM: Rozite, K., D.J. Bezemer, and J.P.A.M. Jacobs, Towards a Financial Cycle for the US, 1873-2014

16014-EEF: Neuteleers, S., M. Mulder, and F. Hindriks, Assessing Fairness of Dynamic Grid Tariffs

16015-EEF: Soetevent, A.R., and T. Bružikas, Risk and Loss Aversion, Price Uncertainty and the Implications for Consumer Search

16016-HRM&OB: Meer, P.H. van der, and R. Wielers, Happiness, Unemployment and Self-esteem

16017-EEF: Mulder, M., and M. Pangan, Influence of Environmental Policy and Market Forces on Coal-fired Power Plants: Evidence on the Dutch Market over 2006-2014

16018-EEF: Zeng,Y., and M. Mulder, Exploring Interaction Effects of Climate Policies: A Model Analysis of the Power Market

16019-EEF: Ma, Yiqun, Demand Response Potential of Electricity End-users Facing Real Time Pricing www.rug.nl/feb